Chapter 6

Overview of the Design of Stellar Interferometers

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6.1 Introduction

An optical interferometer is a large and complex beast, comprised of many active and passive systems. There are many engineering challenges in the design and construction of these instruments including, but not confined to, physical stability, atmospheric seeing, path-length equalization, fringe tracking, dynamic control, and dispersion/diffraction problems.

The engineering driving forces for all interferometers are similar. This, combined with our habit of copying each other, results in the fact that most interferometers resemble one another. In this paper I will attempt to discuss some of the known design problems and describe solutions that the community has used to date.

A good overview of what is required in order to build an interferometer was given by Tango and Twiss (1980). This is a "must read" for any student of the subject.

6.2 What We Would Like to Measure

Let us begin by considering the fringe equation using V to represent the measured visibility, $V_{\rm obj}$ the object's real visibility, and ν the wavenumber $(1/\lambda)$ of the spectral channel with bandwidth $\Delta\nu$. The visibility phase is $\Phi_{\rm obj}$, the phase introduced by the atmosphere is $\Phi_{\rm atm}$, the current baseline is given by B and the observation is at elevation angle θ. Given all of that, we can write

$$I(t,\nu) = 1 + V(t,\nu) \times \frac{\sin\left[\pi\, x(t,\nu)\, \Delta\nu\right]}{\pi\, x(t,\nu)\, \Delta\nu} \times \cos\left[2\pi\, x(t,\nu)\, \nu + \Phi_{\rm obj} + \Phi_{\rm atm}(t)\right] \tag{6.1}$$

where the observed visibility is

$$V(t,\nu) = V_{\rm obj} \times \eta_{\rm atm}(t,\nu) \times \eta_{\rm inst}(t,\nu). \tag{6.2}$$

Here the reduction in visibility due the atmosphere ($\eta_{\rm atm}$) and the instrument itself ($\eta_{\rm inst}$) have been added. The total optical path length difference is given by

$$x(t,\nu) = B\cos\left[\theta(t)\right] + x_{\rm vac}(t) + n_{\rm air}(\nu)x_{\rm air}(t) + n_{\rm glass}(\nu)x_{\rm glass}(t) \tag{6.3}$$

using $x_{\rm air}$ to represent the internal path through air and $x_{\rm glass}$ the internal path through glass along with their respective refraction coefficients. The time dependence of these parameters has been explicitly shown in these equations.

Almost all of the extra terms in these equations have the effect of reducing the measured visibility, and therefore also the signal-to-noise ratio of the scientific measurement. Each of these also imply an electro-optical subsystem within the array in order to reduce the visibility loss. For example: atmospheric wavefront distortions must be removed, or reduced, with tip/tilt servos, or more complex adaptive optics systems; path-length variations need to be tracked using a fringe tracker and delay-line combination; and the amount of air and glass paths needs to be carefully controlled in order to reduce differential dispersion effects.

I will try and deal with the most important areas of visibility loss and their solution, or reduction.

6.3 Logistics

In order to do all the science we would like to do, an interferometer requires baselines several hundred meters long, or even larger. The light from each telescope needs to be brought into a central beam-combining facility, which itself must include space for delay lines large enough to compensate for the geometric delays imposed by such long baselines. All of this means a logistic nightmare for the designer of the system. Large amounts of land are required, hopefully flat, and the other elements of the infrastructure, like power, communications and transport, must somehow fit in around the interferometer.

One would like to have a large piece of flat land at high altitude. Unfortunately mountains tend to have more vertical real estate than desired, adding to the logistics problem. It has been the trend to date to place interferometers on an existing observatory site. This tends to further complicate the placement of the various systems, since the existing facilities are rarely transparent, but fortunately it means that most of the other necessary things are

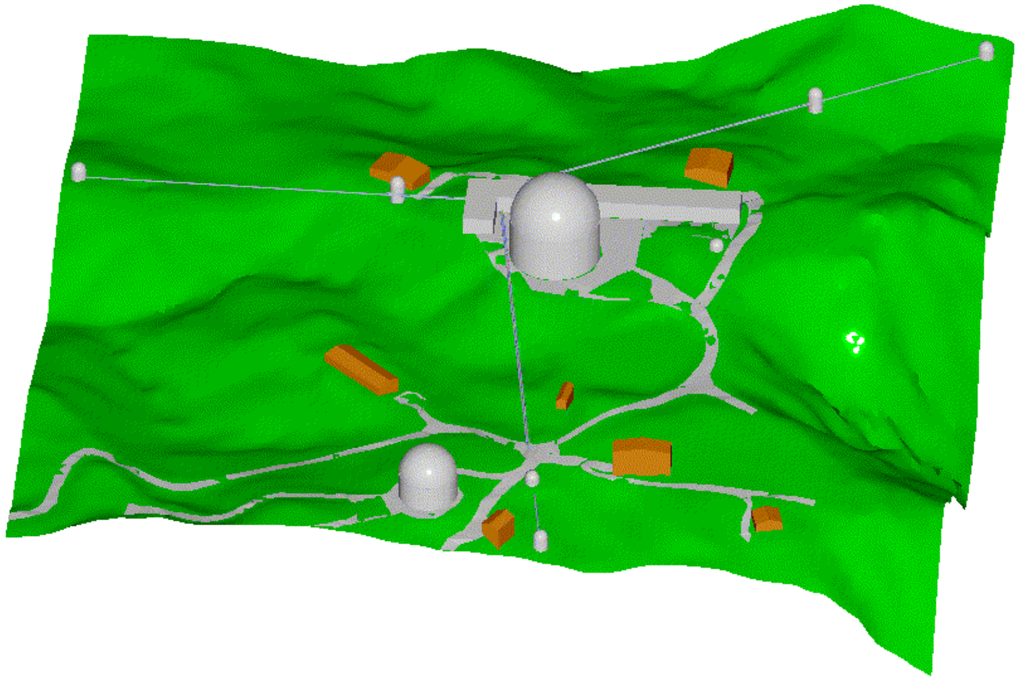

Figure 6.1: Computer aided drawing of the terrain at Mount Wilson, with beam transport pipes for the CHARA Array indicated.

already in place, like a place to sleep, roads, and so on. As an example, the arrangement of the arms of the CHARA Array at Mount Wilson is shown in Figure 6.1.

Until we have solved all the problems associated with using optical fibers for beam transport, you will need to have a line of site between each input aperture and the central building. Deciding where to put each aperture will become a matter of juggling (u, v) plane coverage, light pipes and existing structures and dirt. There is no simple solution to this other than having good survey data, patience and a good three-dimensional modeling package.

6.4 Concrete and Steel

An interferometer has engineering tolerances of the same order as the wavelength at which it will operate. This means everything must either have an active optical system for correction or be stable at the micron level. It is for this reason that you will find a lot of concrete and steel at any interferometric site. The depth of typical concrete foundations is shown in Figure 6.2, which is a photograph taken at SUSI in the early stages of construction.

Not only do you need to use large inertial masses but you need to isolate them from any local sources of vibration. Thus you must ensure that the concrete holding up the building is not the same as that below the optical tables or delay line. You don't want people walking, and therefore vibrating, the flooring below the optical systems. Telescope enclosures should not

Figure 6.2: Preparations for pouring the siderostat foundations at SUSI.

be coupled to telescope support systems. Not being careful about these things will mean you end up with a very sensitive seismic monitor and not an interferometer.

6.5 The Problem with the Atmosphere

The atmosphere has an unfortunate habit of changing all the time and it doesn't always behave as theory says it should. Our most common measurements of the condition of the atmosphere are the coherence length r_0 and the coherence time τ_0.

In the case of τ_0 Davis and Tango (1996) have shown, based on the definition of coherence time given by Buscher (1988), that

$$\frac{\overline{C(\Delta t)}}{C(0)} = \frac{6}{5\tau}\left[\gamma\left(3/5, \tau^{5/3}\right) - \tau^{-1}\gamma\left(6/5, \tau^{5/3}\right)\right] \tag{6.4}$$

where Δt is the sample time, the ratio $\overline{C(\Delta t)}/C(0)$ is the correlation loss factor due to this finite sample time, $\tau = \Delta t/\tau_0$, and $\gamma(a, x)$ is a partial gamma function. Davis and Tango (1996) used this equation to measure τ_0 and thereby calibrate out the effects of a finite sample time. To do this you must measure the visibility simultaneously at many sample times and fit these measurements to Equation 6.4. It is then possible to extrapolate back to zero sample time.

The value of τ_0 is in the range of a few milliseconds in the visible during normal seeing conditions and can be as high as several tens of milliseconds in excellent seeing and in the

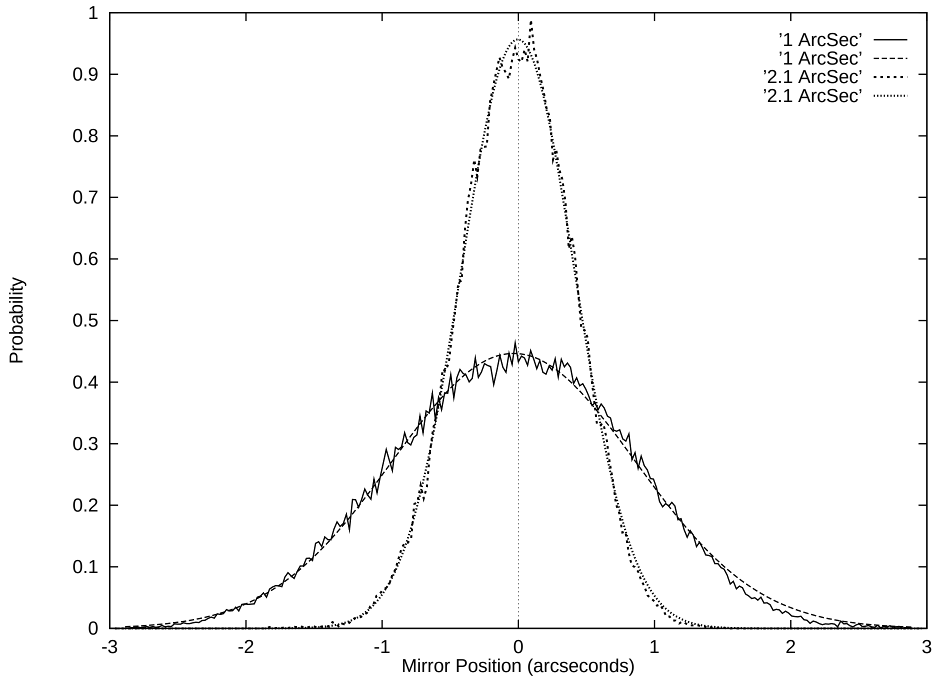

Figure 6.3: Histogram of tip/tilt mirror motion while tracking a star during relatively good (1 arcsec) and bad (2.1 arcsec) seeing. Measurements like this help establish the seeing, both internal and external, during a visibility measurement. These data are taken from ten Brummelaar and Tango (1994).

infrared. This basically sets the time constant for the servo systems within the interferometer. The adaptive optics must run at the rate of hundreds of Hertz in order to keep up with the motion of the atmosphere.

It is also possible to measure r_0 using an already existing subsystem within the interferometer. One possibility is to use the motion of the delay line when locked onto fringes, but this requires locking the system onto fringe phase and will not work if you are scanning through the entire fringe packet or using group-delay tracking. A second, and easier, option is to use the data from the tip/tilt servo. See for example the data in Figure 6.3.

Unfortunately, while many studies of atmospheric seeing have been done over the years (cf. ten Brummelaar *et al.* 1994; Buscher 1994; Haniff *et al.* 1994; Davis *et al.* 1995) it is still not clear how one interprets the spatial seeing data. For the time being, one simply hopes that the optical systems work well, that the internal seeing is negligible, and that things do not change too much between observations of science object and calibrator.

It is, of course, important that the seeing internal to the instrument does not further reduce the visibility. To this end it is common to use "light-pipes" to direct the light from the input aperture, either a siderostat or a telescope, into the central beam-synthesis facility. Often these light-pipes are evacuated in order to remove most of the air and improve the seeing, and will therefore require air-tight windows at either end.